OST TECHNICAL PROGRESS REPORT
TEAM WORK PLAN -- FY2001 RESULTS

TITLE: Combustion and Environmental Research Facility (CERF) Team

TEAM MEMBERS: DOE: Mark C. Freeman (team leader), William J. O'Dowd, Mahendra P. Mathur, and Clement J. Lacher, Jr.   Parsons Infrastructure & Technology, Inc: Gary F. Walbert

DESCRIPTION: The CERF team conducts experimental evaluations that contribute to enhanced fuel, emissions, and/or efficiency performance in pulverized-coal (pc) and other coal combustors. Technical issues include fuel handling, combustibility, ash deposition and heat transfer, and flue gas emissions. Current R&D includes three major thrusts: (1) biomass cofiring for pc applications; (2) high-temperature materials and ash deposition studies; and (3) novel combustion/emissions concepts.

The Combustion and Environmental Research Facility (CERF) can assess the performance of solid, liquid, and gaseous fuels in typical pc systems, as the basic design criteria for the 500,000 Btu/hr CERF achieves similarity with full-scale utility boilers. Efforts support existing pc combustors as well as advanced power systems that are currently under development. The CERF team works with outside parties that bring fuels, concepts, equipment, and/or materials for evaluation. The team objectives are to obtain basic information that supports large-scale or utility test burns and to provide a test bed to screen lab-scale concepts. Experimental data is also used to validate and help develop various combustion/flow models.

Commissioned in 1989, the 500,000 Btu/hr CERF was designed to achieve similarity with full-scale utility boilers to replicate typical specification ranges for burner relative mass flow, radiant furnace temperature distributions and gas residence time, and convective section gas velocity. Although pilot-scale combustors cannot exactly duplicate conditions in utility boilers because of inherent distortions, such as heat release rates and surface-to-volume ratios, they have proven to be useful in examining the integrated effects of a number of interdependent design/operating variables. Fuel quality can be assessed by comparing its pilot-scale performance with that of reference fuels for which full-scale performance is known. The CERF is equipped to evaluate various fuel characteristics: (1) transport, handling, and storage, (2) combustibility, flame stability and carbon conversion efficiency, (3) ash deposition rates, heat transfer properties (e.g., emissivity and thermal conductivity), and deposit removal characteristics (e.g., sootblowing requirements), and (4) flue gas emissions, such as SO_2, NO_x, CO, total hydrocarbons, and particulates.

In conducting various R&D projects, the CERF team closely interacts with other NETL/OST teams (e.g., the Clean Air Team and the Materials Team) and personnel with respect to experimental and modeling work.

RESEARCH OBJECTIVES: R&D work is based on three objectives: First, provide data to assist in the evaluation of biomass cofiring and other interrelated combustion/environmental issues (including trace emissions and $PM_{2.5}$) associated with pc combustors. Second, develop a better understanding of the fireside combustion and heat transfer materials issues associated with higher gas temperatures, higher tube temperatures, and various gas environments that will drive and form the basis of advanced power systems. Third, evaluate other novel combustion/emissions concepts.

LONG TERM GOALS / RELATIONSHIP TO NETL'S PRODUCT LINES: The CERF Team activities support a number of NETL Product Teams, including (1) Combustion Systems Product Team; (2) Environment Product Team; (3) Advanced Research/Power Product Team. Some team activities have also provided technical support to the Clean Coal Technology Program as well as Solid Fuels & Feedstocks, New Business, and International Programs. In addition to NETL internal funding from the Office of Fossil Energy (FE), the CERF Team receives funding from the DOE Office of Energy Efficiency and Renewable Energy (EERE) Biomass Power Program and the EERE Biomass Transportation Fuels Program. This EERE funding enables additional activities with respect to the cofiring of various biomass feedstocks and advanced concepts, such as lignin cofiring and ethanol/power co-production.

The CERF team frequently works with external researchers at universities, industrial firms, and other DOE national laboratories. This collaboration enables leveraging with external organizations that receive DOE (FE and EE) funding and other federal funding, such as the U.S. Department of Agriculture (USDA). This allows the team to contribute to a number of projects while working with a limited budget. Our experience has been that these outside project participants request CERF support/testing to extend the scope of their activities.

In-House Research Approach The CERF research approach builds upon prior efforts and accomplishments, while broadening the collaborative research interactions and leveraging with external organizations, including the EPA, other federal entities and DOE National Laboratories, local/municipal, and state organizations, and various universities, small businesses, utilities, and manufacturers. In recent years, the CERF staff has interacted with over 20 government, university, and private sector firms in the planning, conduct, and publishing of research.

Research is based on enhancing the scientific understanding of technical issues and developing and evaluating advanced technologies in the laboratory, in pilot-scale facilities, and in the field. Experimental data are being used in conjunction with science-based computational modeling and process economic/systems studies. Research priorities reflect, in part, proposed regulations and requirements being discussed relative to Hg and other hazardous air pollutants (HAP), $PM_{2.5}$, regional haze, toxic release inventory (TRI), utilization of coal combustion by-products (CCB), and renewable portfolio standards (e.g., biomass cofiring) that could have an impact on coal utilization.
CERF research supports issues of interest to existing coal-fired boilers and is intended to be relevant to high-efficiency advanced power and Vision 21 systems under development, since the associated emission targets of these are much more stringent than those of currently operating power plants.

SUMMARY ACCOMPLISHMENTS The CERF team supported a number of activities with external organizations. FY01 results are summarized for each activity as well as the underlying motivation and future plans for the ongoing combustion and environmental issues.

PM2.5 Dilution Sampling Research During FY01, CERF testing enabled $PM_{2.5}$ dilution sampling 'source fingerprinting' studies using unique instrumentation to support DOE/NETL University Coal Research and the DOE/NETL Advanced Research & Environmental Technology (AR&ET)

Program in project teams led by Carnegie Mellon University (CMU). The CERF is functioning as a host site for dilution sampling to assist NETL Contracts DE-FG26-99FT40583 and DE-FC26-01NT41017 with an overall collaboration among 20 research groups from 15 universities and 2 companies to pull together advanced research in ambient air characterization, source apportionment modeling, and other scientific approaches to address air quality issues.

Dilution sampling source fingerprint experimental data is needed to develop advanced models with neural networks to tie-together the extensive R&D being conducted (funded by DOE/NETL and EPA) to evaluate ambient $PM_{2.5}$ characterization and source apportionment. Essentially, the dilution sampling technique simulates the mixing, aerosol condensation, etc. that occurs when stack plumes are discharged to the atmosphere. More importantly, this enables sophisticated ambient air monitoring equipment (like that installed at DOE/EPA Supersites) to be located at combustion sources, so particles can be carefully collected and characterized to update 'source fingerprints'. For example, the University of Maryland (UM) has developed a novel adaptation of laser induced breakdown spectroscopy (LIBS) for single particle characterization of 15 metals simultaneously. The CERF tests represented the first field evaluation of the UM LIBS technique for multi-metal single particle characterization in coal-fired applications to build upon prior research that involved single-metal single particle characterization for glass making applications at SNL-Livermore.

Ultimately, researchers want to be able to better determine the origin and mechanisms that lead to primary and secondary $PM_{2.5}$ so that models can more accurately be used to assess 'what if?' scenarios in evaluating regulatory policies and developing control technologies for $PM_{2.5}$ that would impact coal-fired generation.

During the first half of FY01, CERF tests were conducted to help CMU shakedown, evaluate, and refine the $PM_{2.5}$ dilution sampling technique based on the initial CERF testing that began in FY00. CERF testing primarily used the low-sulfur Prater Creek bituminous coal and allowed $PM_{2.5}$ characterization both upstream and downstream of a pulse-jet baghouse. As part of these tests, CMU was able to obtain continuous measurements of particle size from 3 nm to 20 microns. CMU was able to demonstrate excellent repeatability with the technique, with standard deviations below 10% of the mean for intraday sampling for various measurements and within 25% of the mean when comparing sampling results for different test days.

The CERF July 2001 test program included a number of coals - two bituminous coals (a moderate-sulfur Pittsburgh seam coal and a low-sulfur eastern Kentucky coal) and one low-sulfur Wyoming Powder River Basin subbituminous coal. Operating conditions (adjusting load, NO_x, and unburned carbon) were also examined, including biomass (pallet wood) cofiring as part of the 'source fingerprinting studies'. To complement $PM_{2.5}$ dilution sampling studies during the July test, NETL staff acquired Hg emissions data using the Sir Galahad Continuous Emissions Monitor (CEM), as well as detailed furnace sampling characterization of temperature, gas composition, and particle burnout profiles.

During FY01, two presentations were made at national conferences based on the CMU/NETL project. This included "Effect of Sampling Conditions on Primary Particulate Matter Emissions from a Pilot-Scale Coal Combustor" at the American Association for Aerosol Research (AAAR) Nineteenth Annual Conference, November 6-10, 2000 in St. Louis, Missouri, and "Sampling, Analysis, and Properties of Primary $PM_{2.5}$: Application to Coal-Fired Utility Boilers" at the DOE/NETL University Coal Research Program, June 5-6, 2001 in Pittsburgh, Pennsylvania.

During FY02, project participants were planning on pilot-scale CERF testing to complete the dilution sampling study on the CERF to support NETL Contracts DE-FG26-99FT40583 and DE-FC26-01NT41017. Experiments will determine $PM_{2.5}$ emissions from NETL combustors as a function of dilution rate, temperature, and relative humidity. Samples will be analyzed for basic size distribution and composition of emissions, emission rates of nanoparticles and elemental and organic carbon, and the hydrophilic properties of the particles. Exploratory smog chamber experiments will examine the physiochemical transformations of gaseous and particulate matter. After completing the dilution-side research, work will be completed on the investigation of source-side impacts on primary and secondary $PM_{2.5}$ formation, including changing fuels (coal and biomass with differing volatile matter, ash composition, etc.), combustion conditions (e.g., unburned carbon, total hydrocarbons), control technologies (e.g., low-NOx burner, SNCR), and emissions levels (sulfur and nitrogen oxides, ammonia slip).

The results from the CERF sampling experiments will form the basis for a comprehensive sampling methodology for other aerosol point sources. After the CERF test program is completed, researchers will conduct field work using the novel dilution sampling equipment to update 'source fingerprints' for coal-fired utilities, steel and coke plants, and other industries (e.g., meat packing plants), as well as for transportation vehicles.

FY02 CERF testing may be conducted to help refine the new CMU $PM_{2.5}$ dilution sampling design, methodology, and equipment in terms of carefully balancing/controlling flows of slipstreams, dilution tunnel, residence time tanks, etc., as well as the interface with sensitive/complex instrumentation, including on-line particle size/composition analyzers in addition to conventional filter-based techniques. It will be important to make the system somewhat more compact to enable subsequent field studies.

An additional aspect of the project concerns the possibility of co-locating dilution samplers from other research organizations in the U.S. or abroad, as well as other sampling equipment, in an effort to develop improved protocols. Of particular interest is developing a standard for dilution sampling based on a sound scientific understanding of the cause and effect relationships with sampling parameters, such as mixing and residence time, for various applications. In addition, it is important to evaluate and develop improved methods for minimizing inherent biases (e.g., losses from condensible organics) in conventional stack sampling methods that utilize heated filters, where filter loadings may be temperature dependent. For example, species existing in the gas phase at elevated in-stack temperatures may actually transform into fine particulates/aerosols at ambient conditions, thus creating a situation where in-stack loadings would be underreported relative to what could be collected at lower temperatures. Such research would help enable the development of improved field sampling methods (with reasonable cost) that reduce biases and have better agreement with expensive, research-grade equipment.

Biomass Cofiring Research Team efforts have concentrated on two basic themes: (1) Evaluating the combustion and emissions characteristics of "opportunity" biomass feedstocks, such as treated woods, lignin residues from cellulosic waste-to-ethanol and ethanol/power co-production processes, and animal wastes, where opportunities for significant environmental benefits exist in addition to offering lower fuel costs relative to conventional biomass feedstocks such as sawdust and (2) developing concepts and acquiring fundamental data to allow the inclusion of opportunity fuels (e.g., certain biomass and other feedstocks with high-tipping fees) with lower delivered fuel costs (on a $/MMBtu basis compared to raw coal) which could improve overall economics, while addressing other environmental benefits.

While the importance of the two themes (above) are widely understood and represent 'core technical needs' to Vision 21 concepts, the inclusion of opportunity fuels as a third goal may sometimes be an afterthought. The role that opportunity fuels could play in coal-based Vision 21 systems could be significant, particularly considering various actions already underway that would impact power generation in 2010 and beyond.

Because 14 states have recently adopted various forms of renewable energy portfolio standards, calling for 3-fold to 8-fold increases from current 2001 levels in power generation and purchases from nonhydro renewables by 2009-2012, cofiring is gaining momentum as a means of utilizing the existing infrastructure of coal-fired systems to increase biomass energy at reasonable capital costs (typically $50-300/kW). In addition, various renewable energy standards and an expansion of tax incentives have been proposed in recent years, and many expect that federal legislation will eventually be passed to encourage at least a tripling of nonhydro renewables by 2010. Present IRS Section 29/45 tax incentives (about $0.015/kW-hr) apply to biomass gasification and closed loop systems where biomass is grown purposely for energy use, but steps may be taken in the future to include open loop tax incentives (perhaps in the range of $0.005-0.01/kW-hr) for cofiring biomass wastes, such as sawdusts, urban waste wood, municipal wastes, and other residues from forestry, agricultural, and other industrial sources.

Clearly, the combination of new and/or strengthened state and federal renewable energy portfolio standards, as well as expanded tax incentives, may considerably broaden the applicability of opportunity biomass fuels as a consideration for new Vision 21 plants in the decades ahead.

Treated Wood Cofiring Treated wood cofiring test results from the CERF were published in December 2000 in a special biomass cofiring issue of <u>Biomass & Bioenergy</u> (Elsevier). The paper was entitled "Pilot-Scale Air Toxics R&D Assessment of Creosote-Treated and PCP-Treated Wood Cofiring for Pulverized Coal Utility Boiler Applications". The results and some preliminary economics were also presented in the paper entitled "Pilot-Scale Cofiring Results of Treated Woods and Other Biomass Fuels for Coal-Fired Boiler Applications" at Bioenergy'2000 in Buffalo, NY during October 15-19, 2000. In addition, the CERF test results were also featured in the September 5, 2000 edition of the DOE Pulse - an on-line publication of research highlights from DOE National Laboratories. The story was subsequently picked up by a British publication, <u>Chemical Engineer</u>, which published an article entitled "Wood is Good" in the October 5, 2000 issue.

At this juncture, one may ask "why the interest in treated woods and the NETL study?" CERF cofiring tests were conducted with pentachlorophenol-treated (PCP) and creosote-treated utility transmission poles in a comprehensive air toxics project involving DOE's Office of Energy Efficiency and Renewable Energy (EE) Biomass Power Program, Foster Wheeler (FW), Cofiring Alternatives, Sithe Energy (former GPU) Seward Station, EPRI, Entropy, ACHD, and the Pennsylvania State Department of Environmental Protection (PA DEP). The CERF tests showed that treated woods could be successfully cofired at 10% energy basis without increasing hazardous air pollutants (HAPs), including heavy metals, dioxins, furans, PAH, aldehydes, ketones, other volatile organic compounds, and total hydrocarbons. In many instances, trace organic emissions were near or below detection limits, while treated wood cofiring showed reductions in SO_2, NO_x, and particulates. The results clearly indicate that treated woods can be successfully cofired with pulverized coal. The CERF testing measured 'uncontrolled emissions' (upstream of flue gas cleanup devices) factors to compare treated wood cofiring with an Upper Freeport bituminous coal. But treated wood cofiring could be equally, if not more attractive, from a practical control standpoint where various pollution control technologies, such as wet scrubbers, spray dryers, fabric filters, and electrostatic precipitators (for SO_2, NO_x, and particulate control), can provide secondary benefits for removing some trace pollutants.

The CERF baseline coal results were generally consistent with air toxics data reported from coal-fired utility boilers. As a result of this test data, it is expected that utilities and regulators will be able to address critical pre-permitting issues to cofire treated wood, including utility generated wood, telephone poles, railroad ties, etc. Treated-woods are potentially attractive opportunity fuels for cofiring because of high disposal costs (upwards of $80/ton) and large numbers throughout the U.S.

Since publishing the CERF air toxics test results, a number of inquiries have been received from government and industrial organizations in the U.S. and abroad. Efforts have been initiated with a number of organizations to consider the NETL CERF test results so that scale-up demonstrations and technology transfer could occur. Discussions are also underway for possibly using the CERF data to help develop emission factors for biomass cofiring of coal, since such emission factors presently do not exist.

Animal Waste Cofiring Feedlot manure is a renewable fuel resource with more than 110 million tons of cattle and poultry manure produced annually. The feedlot cattle industry is a major industry in the southern Great Plains states and other farming areas of the United States. The Texas panhandle area alone accounts for 6.3 million heads (85% of total cattle in Texas) producing 18 million tons of fresh cattle manure annually. The runoff water from feedlots may contain bacteria, while the stored animal manure anaerobically releases CH_4, NH_3, H_2S, amines, volatile organic acids, mercaptans, esters, and other chemicals. The waste, if stockpiled rather than utilized in fertilizer for grain crops or other applications, poses economic and environmental liabilities. Thus, the feedlot manure issues involve a number of environmental, safety, and health issues, including the release of greenhouse gases like CH_4 from natural manure decomposition, contamination of drinking water and waterways, the spread of diseases by rodents and insects, and fires.

During FY01, a number of papers were published in conference proceedings and submitted to journals to discuss CERF feedlot manure cofiring test results using a Wyoming Powder River Basin (PRB) subbituminous coal. This testing has been conducted under a Cooperative Research and Development Agreement (CRADA) with Texas A&M University. The project also involves State of Texas Advanced Technology Program, New Centuries Technology/Southwest Public Services Company (SPSC), Texas Cattle Feeders Association, and the DOE Western Regional Biomass

Energy Program. SPSC is considering feedlot manure cofiring at its Harrington and Tolk Stations with a combined capacity of 2,200 MWe.

Prior CERF testing was conducted to verify Texas A&M preliminary bench-scale testing, which showed a slight increase in SO_2 and NO_x relative to a baseline Wyoming PRB coal, although the high-volatility of the manure helped minimize this increase based on a lower NO_x conversion relative to its fuel nitrogen content that is about 6 times higher on an equivalent energy basis than the PRB coal.

Conventional manures may have ash contents in excess of 40-45 wt% and be over an order of magnitude higher in ash loading on an equivalent lb/MMBtu basis than many coals. Despite their very high ash contents, CERF cofiring tests showed good combustibility, as evidenced by reasonable unburned carbon profiles for furnace samples taken at different distances from the burner (i.e., similar to representing different residence times), as well as analyses of bottom ash and fly ash samples.

However, the CERF tests showed slagging/fouling difficulties with conventional manure cofiring even at reduced furnace exit gas temperatures (FEGT) in the range of 1900F. For example, ash loading increased by about 66% in the CERF cofiring tests that were conducted at 10% mass (4.4% energy) basis. In addition, the ash composition/chemistry (e.g., high potassium, phosphorous) and relatively high chlorine with conventional feedlot manures are also of concern relative to other biomass feedstocks. For this reason, improving the fuel quality of feedlot biomass was a major thrust in FY01 efforts at Texas A&M under the CRADA, in order to significantly reduce ash contents.

As a result of testing conducted under the CRADA, an exciting development in FY01 was research conducted by Texas A&M using advanced manure handling procedures to improve feedlot biomass fuel quality for planned CERF cofiring and reburn tests in the spring of 2002. This research has successfully incorporated coal combustion byproducts (CCB)-paved feedlots to reduce the manure's ash content by nearly four-fold on an energy basis, while offering potential new markets for the sale and application of utility fly ash. In addition to providing combustion/emissions benefits during cofiring, the CCB-paved feedlots reduce groundwater contamination and airborne dust relative to conventional unpaved feedlots.

Engineering Design of CERF Reburn System During FY01, extensive design activities continued for a fuel flexible reburn system for NOx control at the CERF, while incorporating other features such as ammonia injection (e.g., selective noncatalytic reduction, SNCR) and exploring concepts for enhancing reburn performance. Published research by various organizations, such as General Electric-Energy and Environmental Research (GE-EER), have shown promising results for biomass reburn owing to the high volatility of biomass fuels in tests comparing NOx reduction results with other reburn fuels, such as natural gas and coal. Although many biomass fuels (e.g., sawdust) have relatively low nitrogen contents, other biomass fuels have very high nitrogen contents. While high nitrogen content biomass fuels will normally increase NOx when directly cofired into pulverized coal flames, possible enhancements in NOx reduction could occur at sufficiently low injection temperatures similar to SNCR-type reactions. In addition, some of the biomass fuels with relatively high ash contents and unique ash chemistry may also promote certain NOx reduction mechanisms, although ash loading from a slagging/fouling perspective may be a limiting practical factor as discussed above. This is the basis of some bench-scale 100,000-Btu/hr reburn tests using high nitrogen (with naturally present NH_3) feedlot biomass conducted by Texas A&M last year.

FY01 CERF reburn design activities centered on modifications of the process control and data acquisition software, along with new safety interlocks, in addition to the typical updates of the standard operating procedure (SOP), process & instrumentation drawings (P&ID), and modification of the gas injection panel and instrumentation. In addition, activities addressed a number of key components. First, extensive tests were conducted using various biomass and other fuels of varying density, particle size, and moisture with the cooperation of several industry vendors offering various feeder designs, including rotary, vibratory, and screw-type. This testing included cold-flow evaluations of loss-in-weight feeder fluctuations, as well as the videotaping of feeder discharge and short duration CERF cofiring tests in which furnace oxygen fluctuations and in-situ flame viewing of burner behavior were performed using NETL's novel optical borescope probe. This testing was essential in terms of ensuring that steady feeding could be achieved in a manner consistent with reburn applications where stoichiometry could be carefully controlled with minimum fluctuations from the feeder discharge and eductor system for transporting biomass fuels. This testing included various operational adjustments, such as hopper inventory, vibratory and/or bed agitation, feedscrews of different flight patterns and diameters, and rotational speed. After this testing, a loss-in-weight feeder system manufactured by K-Tron (dual opposed screw type) was selected and installed on the CERF.

Present limitations on the system include a relatively small hopper above the feedscrew which requires frequent filling (currently manual) and the lack of a sealed transport system to convey fuel directly from drums to the K-Tron hopper. CERF staff have been working with K-Tron on different configurations during the last year, and it is expected that a final system will be installed in early 2002. This sealed system would allow reburn/separate injection tests with manure and other biomass fuels (e.g., treated woods) that may benefit operations to minimize fugitive dust in the plant in light of operator personnel protection equipment (PPE) requirements, as well as avoid more costly improvements to plant ventilation systems.

FY01 activities also included making engineering designs to reburn fuel and overfire air injectors with different configurations and nozzle tips to enable fuel dispersion studies during upcoming CERF tests in 2002. Because of the CERF furnace dimensions (20-inch internal diameter and 9-foot length in the radiant combustor), it is desired to develop options for addressing fuel dispersion and mixing issues in reburn applications. Preliminary 3-dimensional computational fluid dynamics (CFD) modeling using Fluent was also undertaken to help address design and operational issues. In conjunction with mixing and local stoichiometry issues, efforts were undertaken to examine different injectors and options for the main pulverized coal burner at the CERF. In contrast to baseline operations on natural gas, where small pilot-units like the CERF have little difficulty achieving minimal furnace profile variations in temperature and gas composition, in the radial and angular dimensions for a given axial distance from the burner, baseline variations in furnace profiles are much more difficult with coal-fired operations in which discharge and mixing of coal particles/primary air with swirling secondary air creates much more turbulence. For this reason, it is common for initial reburn experiments to use baseline operations on natural gas (and spiking to different baseline NOx levels) with separate reburn injection of biomass or other solid fuels. While the upcoming CERF tests will incorporate this approach, it is desired to conduct biomass reburn tests with baseline coal operations in order to allow other evaluations to occur, such as slagging/fouling measurements and reburn impacts on other emissions, such as mercury speciation and fine particulates.

Development and Validation Tests of 3-Dimensional Computational Fluid Dynamics (CFD) Modeling for Biomass Cofiring During FY01, a number of papers were published in conference proceedings and submitted to journals to evaluate biomass particle size and other impacts relative to unburned carbon, NOx, and operational issues, such as the avoidance of unwanted, still-burning sparklers entering bottom ash or convective sections in cofiring and reburn applications. This project builds upon a collaboration with Sandia National Laboratory-Livermore's (SNL) bench-scale (100,000 Btu/hr) Multi-Fuel Combustor. During FY99/00, SNL data was used in a project with Carnegie Mellon University (CMU), NETL, and Fluent, to develop a 3-D computational fluid dynamics (CFD) model for evaluating biomass cofiring design and operational issues based on a comprehensive approach to devolatilization, char conversion, and heat transfer, along with gravitational, buoyancy, and drag forces that influence particle trajectories in a swirling flow.

With respect to CFD modeling, it is important to note that comparatively less experimental data exists to describe the devolatilization and char conversion of various biomass opportunity fuels over a wide range of conditions as compared to coal, where extensive research has been conducted. In fact, the very definition of pulverized coal (pc) boilers implicitly carries with it a well-known range of coal particle size distributions achieved by the pulverizers, which also serve to impart an important drying function prior to burner injection in wall-fired, roof-fired, and tangentially-fired boilers. In short, pulverized coal has come to mean a "universally recognized" standard of about 70% minus 200-mesh (74 micron) - with perhaps only plus or minus 10% based on coal rank and boiler design - with less than 2% plus 50-mesh based on the residence time requirements, furnace temperatures, and mixing/velocity profiles in existing boilers.
&&&&&&&&&
In contrast, biomass cofiring in pulverized coal boilers, as well as in pilot facilities, has shown considerable differences in certain instances. For example, differences show up in maximum biomass particle topsizes, in relationships between NOx reductions and percent cofiring, and in unburned carbon levels. These differences in results may be attributed to ignition and char burnout influencing heat release, as a result of varying particle trajectories, or as a result of different residence times associated with the type, size distribution, and moisture of biomass fuels.

In short, the answer to "how much, how wet, how big, and injection location?" may be furnace specific when considering biomass cofiring and preliminary reburn design. Thus, one needs to address issues such as sensitivities with moisture, particle size, initial aspect ratio, and volatile yield of biomass. CFD modeling simulations allow the tracking of the 'fate of the particles' and clearly show that, whereas some biomass particles of different sizes and moisture may stay in the boiler at similar residence times (e.g., 1.5-3 sec) as the pulverized coal, other particles may achieve much longer (e.g., up to 6 sec) or shorter (unburned particles that drop quickly into the bottom ash) residence times due to trajectory considerations in the swirling flow field.

During FY01, CERF biomass cofiring validation tests for Fluent™ 3-D CFD modeling were initiated using the new feeding system for separate injection of biomass fuels to complement earlier cofiring testing with coal/biomass blends (simulating co-pulverization). The new feeding system allows for injection of a wide range in biomass firing rate, particle size, and moisture. As part of this testing, a new 3-screen system was installed to allow further examination of particle size effects, where the usual biomass fuel could be separated into different fractions with more tightly segregated size distributions.

CERF testing has included furnace sampling profiles in radial and axial directions in order to assess char burnout and evaluate local stoichiometry effects due to varying distribution of fuel particles from the burner and mixing effects. Efforts were also undertaken to adjust injector design and burner operation in order to improve fuel particle distribution and mixing and thus reduce profile variations. In the future, analytical characterization of char samples could be determined to compare aspect ratios with CFD model predictions in furnace profiles during biomass combustion/cofiring.

This research also includes CFD simulations of other facilities, including full-scale utility boilers, to assist in the evaluation of biomass particle size issues in conjunction with process economics for biomass fuel handling. In addition, continued technical assistance is provided to firms, such as Mesa Reduction Engineering and Processing (MREP), that are developing prototype coal/biomass mills and seek fuel characterization, such as size distribution for coal/biomass co-pulverization tests.

Lignin Cofiring and Ethanol/Power Co-Production During FY01, project planning continued for upcoming CERF lignin cofiring tests. Various organizations, including TVA, EPRI, NREL, and EERE, as well as industrial firms, are seeking to develop and commercialize novel processes to convert cellulosic wastes into 5-ring and 6-ring sugars that can subsequently be fermented to ethanol. However, cellulosic wastes (MSW, wood chips, rice hulls, bagasse, almond prunings, etc.) contain lignin, which resists acid treatment and is not convertible to sugars. A market for lignin by-product must be found for the process to be economic, since the lignin can represent over 50% of the heat input. Lignin has a relatively high heat content (about 8,000-12,000 Btu/lb dry basis, depending on ash content) although its very fine particle size makes it difficult to dewater with conventional equipment. The potential of the ethanol/power co-production technology is substantial. A modest 25 million gallon per year ethanol plant could produce enough lignin to provide 10% of the thermal input to a 400-MWe coal-fired boiler with a 65% capacity factor.

During FY01, TVA operated a pilot plant in Muscle Shoals, Alabama to produce ethanol from forestry residues using a dilute acid process. This pilot plant testing resulted in about 900 lbs (dry basis) of by-product lignin for CERF cofiring tests planned for early FY02. The CERF lignin cofiring tests will use a baseline coal blend, consisting of 80% Colorado bituminous coal and 20% Wyoming PRB coal, from TVA's 1200-MWe Colbert coal-fired station. The CERF lignin cofiring tests will be compared to pilot scale cofiring results performed at the Energy and Environmental Research Center-North Dakota (EERC-ND). These latter tests used a lignin derived from municipal solid waste (MSW). The lignin was prepared by Masada Resource Group's concentrated acid process along with treated biosolids from a pretreatment step involving sewage sludge. The planned EERC-ND and CERF cofiring tests will use a similar Colorado/PRB coal blend and test matrix so that cofiring results can compare the characteristics of lignin derived from the muncipal versus forestry waste. A key emphasis of the lignin cofiring is to evaluate combustibility, emissions, and slagging/fouling impacts in order to help build a lignin database relative to other biomass fuels available for cofiring.

In addition, the upcoming work will support an ethanol/power co-production feasibility study and preliminary design package. NETL researchers will also help assess improved additive packages (e.g., extension of NETL's patented GranuFlow process) for dewatering/agglomeration to improve lignin handling and allow backmixing and co-pulverization with coarse coal. Other R&D issues concern the avoidance of sugar loss (to maximize fermentor yield) during the lignin separation/dewatering, treatments for neutralizing residual acid, and the possible use of lignin as a biomass additive/binder for waste coal briquettes.

Publications & Presentations

Annamalai, K., Sweeten, J., Freeman, M., Mathur, M., O'Dowd, W., Walbert, G., and Jones, S. (2000). Pilot plant testing of cattle feedlot biomass cofiring in a 500,000-Bbtu/hr DOE-NETL pulverized coal combustor. Proceedings of Seventeenth Annual International Pittsburgh Coal Conference.

Freeman, M., O'Dowd, W., Hargis, R., Jr., Brown, T., James, R., Plasynski, S., Walbert, G., Lowe, A., Dunder, T., Tillman, D., Battista, D., Jr., and Costello, R. (2000). Pilot-scale air toxics results for pcp/creosote-treated wood cofiring for pulverized coal combustion applications. Proceedings of the Seventeenth Annual International Pittsburgh Coal Conference.

Gera, D., Freeman, M., O'Dowd, W., Mathur, M., Walbert, G., and Robinson, R. (2000). Computational fluid dynamics modeling for biomass cofiring design in pulverized coal boilers. Proceedings of the 9th Biennial Bioenergy Conference.

Freeman, M., O'Dowd, W., Goldberg, P., Plasynski, S., and Walbert, G. (2000). Pilot-scale cofiring results of treated woods and other biomass fuels for coal-fired boilers. Proceedings of the 9th Biennial Bioenergy Conference.

Freeman, M. C., O'Dowd, W. J., Brown, T. D., Hargis, R. A., Jr., James, R. A., Plasynski, S. I., Walbert, G. F., Lowe, A. F., and Battista, J. J., Jr. (2000). Pilot-scale air toxics R&D assessment of creosote-treated and pcp-treated wood cofiring for pulverized coal utility boiler applications. Biomass & Bioenergy. ?: Pergamon-Elsevier.

Gera, D., Mathur, M., Freeman, M., and O'Dowd, W. (in press). Moisture and char reactivity modeling in pulverized coal combustors. Combustion Science and Technology.

Gera, D., Mathur, M., Freeman, M., and O'Dowd, W. (2001). Effect of moisture and variable char reactivity on biomass/coal cofiring units. 2001 Joint International Combustion/American Flame Research Committee Symposium.

Gera, D., Mathur, M. P., Freeman, M. C., O'Dowd, W. (2001). On the CFD analysis of 500,000-Btu/hr combustor using enriched O2 and recycled flue gas. 2001 Joint International Combustion/American Flame Research Committee Symposium.

Annamalai, K., Sweeten, J., Freeman, M., Mathur, M., O'Dowd, W., Walbert, G., and Jones, S. (To be submitted). Co-firing of coal and cattle feedlot biomass (fb) part iii: Performance results from a

500,000-Btu/hr pilot plant scale boiler burner. Fuel.

In addition to the above technical presentations/publications, the CERF team also assisted in the preparation of more general articles for magazines, newsletters, and websites, such as Clean Coal Today and DOE Pulse, that target wider audiences in terms of technology transfer and outreach relative to DOE and NETL activities. During FY01, a number of presentations were given in a number of industry forums, including the Electric Power Research Institute's Biomass Interest Group and Upgraded Coal Interest Group. The CERF work was also included in a poster session presented at the May 2001 FE Materials Conference in Knoxville, Tennesssee.